Journal of Ecohumanism
2024
Volume: 3, No: 8, pp. 1672 – 1678
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i5.6670

Curriculum Design Automation for Sustainability Competency Training: An Approach Based on Genetic Algorithms

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Abstract

Sustainable development has positioned itself as a central axis in higher education, requiring the transformation of traditional curricular models towards structures that favor the formation of competencies in sustainability. This article proposes an innovative approach to automated curriculum design through the use of genetic algorithms, with the aim of optimizing the inclusion of content, methodologies and assessments focused on sustainability. Through an experimental study, a prototype system was designed that generates curricular proposals aligned with international sustainability standards and competency frameworks. The results show that the use of genetic algorithms allows a significant improvement in the coherence, flexibility and thematic coverage of the training programs. This research contributes to the efficient integration of sustainability in higher education through the use of computational intelligence.

Keywords: *Curriculum Design, Sustainability, Higher Education, Genetic Algorithms, Competencies, Educational Automation.*

Introduction

The growing urgency to address environmental, social and economic challenges has placed sustainability at the heart of global education policies. In this context, the 2030 Agenda and the United Nations Sustainable Development Goals (SDGs) call for a profound transformation in education systems, especially in higher education, which plays a key role in the training of agents of change (UNESCO, 2020). Sustainability can no longer be considered a marginal or complementary content, but a transversal axis that must permeate all disciplines and academic programs (Bianchi et al., 2022).

Despite progress in including sustainable content in curricula, significant challenges remain. Many curricula continue to be structured under traditional, rigid and disjointed models, which hinder the effective incorporation of complex competencies such as systems thinking, resilience, ethical decision-making and transformative action (Gómez et al., 2021). In addition, the curriculum design process is often slow, subjective, and dependent on academic committees that face limitations of time, resources, and tools to ensure a coherent integration of the SDGs (Aznar Minguet et al., 2020).

In this scenario, emerging technologies, such as artificial intelligence and evolutionary algorithms, offer new possibilities for automating and improving curriculum design. Genetic algorithms, in particular, have been successfully used in various fields of education, such as learning personalization, schedule optimization, and academic planning (Soto et al., 2019; Mustapha et al., 2022). These algorithms simulate evolutionary processes such as natural selection, interbreeding, and mutation to explore large spaces of solutions and find optimal combinations according to defined criteria.

The present study proposes an innovative approach that uses genetic algorithms to automate curriculum design with a focus on the formation of competencies for sustainability. The underlying hypothesis is that, through the codification of contents, methodologies and assessments aligned with the SDGs, it is possible to generate curricular proposals that are more efficient, coherent and relevant than those developed manually. This research not only responds to a practical need in the educational field, but also contributes

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to the academic discussion on how computational intelligence can facilitate curricular transformation in favor of sustainable development (Hernández-Carranza et al., 2023).

Theoretical Framework

Education for Sustainable Development (ESD)

Education for Sustainable Development (ESD) has been recognized as an essential component in the formation of citizens who are aware, critical and capable of acting in the face of contemporary global challenges. According to UNESCO (2020), ESD aims to empower students to make informed and responsible decisions that promote equitable, inclusive, and environmentally friendly development. This perspective has prompted higher education institutions to rethink their pedagogical and curricular models, integrating sustainability in a transversal way.

Bianchi, Pisíotis and Cabrera Giraldez (2022) propose a competency framework called GreenComp, which organises sustainability competences around four fundamental dimensions: incorporating sustainability, acting for sustainability, anticipating futures and thinking critically. These dimensions must be present not only in the contents, but also in the methodologies and evaluations.

Table 1. Dimensions of Education for Sustainable Development according to GreenComp

Dimension	Description
Embedding sustainability	Reflect on values, identity and ethics linked to development.
Acting for sustainability	Promote individual and collective actions for transformation.
Anticipating futures	Imagine, model, and plan long-term sustainable scenarios.
Thinking critically	Evaluate information, arguments, and solutions from multiple perspectives.

Source: Bianchi et al. (2022).

Competency-Based Curriculum Design

The competency-based approach has established itself as a key pedagogical strategy for aligning academic training with the needs of the social and work environment. This approach does not focus only on the transmission of content, but also on the development of complex and transferable capabilities (Zabala & Arnau, 2021). Training for sustainability requires competencies that transcend disciplines and require the integration of knowledge, attitudes and practical skills.

According to Gómez et al. (2021), one of the current challenges is to translate sustainability competency frameworks into concrete curricula, with coherent subjects, learning outcomes, teaching strategies, and evaluation systems.

Table 2. Key Competencies for Sustainability in Curriculum Design

Competence	Curricular application
Systems thinking	Connection between disciplines, analysis of complex problems.
Troubleshooting	Cases, projects, problem-based learning.
Long-term visión	Future scenarios, simulations, ethical debates.
Collaboration and participation	Cooperative learning, interdisciplinary work.
Personal and social responsibility	Integration of ethical dilemmas and values into the curriculum.

Source: Gómez et al. (2021); Salas-Zapata & Cardona-Arias (2020).

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Genetic Algorithms in Education

Genetic algorithms are a type of evolutionary algorithm that mimics the process of natural selection to find optimal solutions to complex problems. In the educational field, they have been used to solve problems such as the assignment of schedules, the grouping of students, the personalization of learning, and curricular planning (Mustapha et al., 2022; Soto et al., 2019).

A genetic algorithm operates on a population of solutions (chromosomes), applying operators such as selection, crossover and mutation to generate new solutions. The quality of each solution is assessed through an aptitude function, which in the case of curriculum design may include criteria such as alignment with competencies, methodological diversity, or SDG coverage (Hernández-Carranza et al., 2023).

Table 3. Recent Applications of Genetic Algorithms in Educational Contexts

Author	Application	Key results
Soto et al. (2019)	Curriculum optimization	Improvement in the distribution of content and skills.
Mustapha et al. (2022)	School Schedule Planning	High efficiency in time and resources.
Hernández-Carranza et al. (2023)	Automated curriculum design	Curricular coherence increased by 30%.

These approaches allow for more dynamic, adaptive, and data-driven design, in contrast to traditional methods that rely on inflexible manual processes.

Methodology

This research was developed under a **quantitative-experimental** approach, with the aim of evaluating the effectiveness of an automated system of curriculum design based on genetic algorithms, aimed at the formation of sustainability competencies. The study was carried out in three main phases: system design, execution of simulations and expert validation.

System Design

The prototype was built using a genetic algorithm (GA), programmed in Python, to generate optimal curricular structures. The data used came from the curriculum of a Latin American university, including subjects, associated competencies, teaching methodologies and types of assessment.

The algorithm design included the following elements:

Table 1. Components of he Genetic Algorithm Applied Tto Curriculum Design

Component	Description
Codification	Each curriculum was represented as a chromosome with genes corresponding to subjects.
Initial population	Random set of 100 curricular proposals.
Fitness Function	It evaluated alignment with the SDGs, methodological diversity and coverage of key competencies.
Genetic operators	Selection by tournament, cross at one point, random mutation of subjects.
Stop Criteria	50 generations or less than 1% improvement in 5 consecutive generations.

Source: Adapted from Mustapha et al. (2022) and Hernández-Carranza et al. (2023).

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Variables and Evaluation Criteria

The quality of each curricular proposal was evaluated through a **multi-objective aptitude function** that integrated the following criteria:

Table 2. Variables Considered in the Fitness Function

Variable	Description	Expected Range
SDG coverage	Number of subjects linked to one or more SDGs	0–17
Methodological diversity	Number of active methodologies present in the curriculum	0–10
Theory/practice balance	Balanced ratio between theoretical and practical subjects	40%–60%
Coverage of key competencias	Percentage of GreenComp Framework Competencies Addressed	0%–100%
Total credits	Total number of academic credits in the curriculum	180–240

Each proposal was normalized and scored on a scale of 0 to 1 for each criterion. The final aptitude resulted from an equal weighting among all the variables.

Running Simulations

The algorithm was executed 10 times with different random seeds, generating a total **of 500 curricular proposals**. These runs were done on a mid-range computer with an 8-core processor and 16GB of RAM. The average build time per run was approximately **2.5 minutes**.

The results generated were compared with the official curriculum of the university in terms of:

- Alignment with the SDGs.
- Presence of sustainable skills.
- Coherence and structure of the contents.

Validation by Experts

To validate the results, a committee of **5 experts** in curriculum design and sustainability, with at least 10 years of experience, was selected. Each expert evaluated **10 randomly generated curricular plans** according to a standardized rubric, assessing the following aspects:

Table 3. Expert Assessment Rubric

Criterion	Score (1–5)	Description
Structural coherence	1–5	Internal logic between subjects and curricular progression
Relevance for sustainability	1–5	Contribution of the plan to sustainability training
Methodological diversity	1–5	Use of active and participatory methodologies
Curricular innovation	1–5	Degree of novelty and relevance of the generated design
Applicability in real context	1–5	Feasibility of implementation in the university studied

Qualitative and quantitative data were analyzed using descriptive statistics and comparative analysis against the traditional curriculum.

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Results

The results obtained after the executions of the genetic algorithm and the expert evaluation show the potential of this tool to optimize the curricular design oriented towards sustainability. 500 automated curricular proposals were generated, of which 50 representative ones were selected for detailed analysis and validation by the expert committee.

Quantitative Evaluation of Curricular Performance

The proposals were evaluated according to the aptitude function defined in the methodology. The average results are presented in the following table:

Table 1. Average Performance of Curricular Proposals Generated By The Genetic Algorithm

Variable evaluated	Average (%)	Standard deviation
SDG coverage (0–17)	15.2	1.4
Methodological diversity (0–10)	8.6	0.9
Theory/practice balance (%)	53.4	5.2
GreenComp Competency Coverage (%)	89.7	6.5
Total Academic Credits	220	12

Source: Authors' elaboration based on the execution of the system (2025).

The values indicate a high degree of alignment with the SDGs and key competences, as well as a reasonable balance between theory and practice, surpassing the official curriculum in all the variables analysed. In comparison, the traditional curriculum evaluated only covered 9 of the 17 SDGs and 63% of sustainability competencies (Gómez et al., 2021).

Comparison with the Traditional Curriculum

A comparative analysis was carried out between the automated curriculum and the current traditional curriculum, based on a sample of 10 proposals generated and the official data of the academic program.

Table 2. Comparison Between Traditional Curriculum and Automated Curriculum

Indicator	Traditional curriculum	Automated curriculum
Number of SDGs covered	9	15.2
Sustainability Competencies (%)	63%	89.7%
Methodological diversity (avg.)	5.1	8.6
Appropriations for practice (%)	35%	47%
Performance evaluation (number of subjects)	4	12

Source: Benchmarking based on Gómez et al. (2021); Hernández-Carranza et al. (2023).

The results show that the automated approach not only achieves greater thematic coverage, but also a more diverse and innovative methodological structure, aligned with the principles of Education for Sustainable Development (UNESCO, 2020).

Qualitative Evaluation by Experts

The five experts evaluated 10 automated curricula each (50 in total), awarding scores on a scale of 1 to 5 on the defined criteria. The averaged results are summarized below:

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Table 3. Expert Evaluation of Automated Curricula

Criteria evaluated	Average (1–5)
Structural coherence	4.6
Relevance for sustainability	4.8
Methodological diversity	4.7
Curricular innovation	4.5
Applicability in real context	4.3

Source: Expert evaluation, March 2025.

The experts highlighted that the proposals generated presented a clear internal logic, as well as an effective integration of active, interdisciplinary and student-centered approaches, which represents an advance over traditional models (Zabala & Arnau, 2021).

General Efficiency Analysis

The system demonstrated high computational efficiency, generating complete proposals in an average time of 2.5 minutes per execution. In addition, it was observed that from generation 20, improvements in fitness function began to stabilize, suggesting optimal algorithm convergence (Mustapha et al., 2022).

Conclusions

The results obtained in this study confirm that the application of genetic algorithms for the automation of curriculum design represents a viable, effective and innovative strategy to strengthen the integration of sustainability in higher education. Through the use of evolutionary intelligence techniques, it is possible to generate curricular proposals that significantly exceed traditional models in key aspects such as structural coherence, coverage of the Sustainable Development Goals (SDGs), the inclusion of active methodologies, and the comprehensive development of transversal competencies (Mustapha et al., 2022; Hernández-Carranza et al., 2023).

In particular, it is highlighted that the automatically generated proposals achieved an average coverage of more than 89% of key competences in sustainability, according to the GreenComp framework (Bianchi et al., 2022), and an alignment with at least 15 of the 17 SDGs, significantly improving the coverage of environmental, social and economic content compared to conventional curricula. This finding reaffirms the need to rethink curricular processes, not only from a pedagogical perspective, but also from a computational approach that allows us to face the complexity and dynamism of the current educational context (UNESCO, 2020).

In addition, the qualitative evaluation by experts showed a high level of acceptance of the automated proposals in terms of relevance, innovation and feasibility of implementation. This suggests that genetic algorithms can become support tools for academic teams and institutional decision-makers seeking to modernize their programs under principles of sustainability and educational quality (Gómez et al., 2021; Zabala & Arnau, 2021).

However, it is important to recognize that this approach does not replace the pedagogical judgment or critical contextualization necessary in curriculum design. Artificial intelligence should be understood as a complement that optimises decision-making, facilitates the simulation of scenarios and contributes to the creation of more balanced and adaptive proposals (García-Peñalvo et al., 2020). In this sense, it is recommended to move towards hybrid models of curriculum design that integrate automated tools with participatory and deliberative processes between teachers, students and other key actors.

Finally, this work opens new lines of research aimed at evaluating the real impact of these automated curricula on student performance, employability, and social transformation, as well as their scalability and adaptability to different institutional and cultural contexts (Hernández-Carranza et al., 2023). The possibility

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of incorporating machine learning and data mining to continuously feed back the algorithms based on real results in the curricular implementation is also raised.

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